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Potential applications for placing concrete in the deep ocean are basically in three areas: in situ construction of seafloor structures, foundations and massive anchors for fixed ocean facilities, in situ hardening of objects on the seafloor, and containment of hazardous substances for environmental protection. This report presents a method for in situ placement of fresh concrete on the seafloor in which concrete is mixed on a surface platform and

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INTRODUCTION

This report presents a method for placing fresh concrete in situ at ocean depths as great as 20,000 ft. The method integrates existing hardware systems that are used daily by the concrete construction industry and offshore oil industry. The concrete materials are handled, mixed and conveyed on a surface vessel using conventional equipment. A drill pipe suspended from the surface vessel is used to transport the concrete to the seafloor. The pipe is handled, positioned and stabilized using techniques employed on drill ships. The concrete flows down the pipe under the force of gravity while the descent rate is controlled by friction. No valves or constrictions are used in the pipeline for flow control as these techniques may cause blockage in the line. By properly selecting the diameter of the pipe for particular concrete mixes and by assuring that the pipeline remains full at all times, it appears that concrete can be placed reliably at deep ocean depths.

The proposed method would greatly extend the state-of-the-art capability to place concrete in the deep ocean. Presently available methods provide the following capabilities: concrete can be placed on the seafloor or in open forms in water depths to about 400 feet; grouts, which are cement slurries or cement-sand slurries, can be placed underwater in open forms to similar depths; also grouts can be placed underwater at much greater depths, thousands of feet, but only if placed in confined spaces where the flow can be controlled by back pressure, as in an oilwell. In general, for most structural applications concrete is superior to grout and costs less. Concrete, which contains larger aggregates than grout, has better structural properties, is heavier and in some cases can be placed without forms which would result in major cost savings.

A modest development effort is required to validate certain engineering assumptions in the proposed concrete placement method. One basic assumption is that a proper mix design can be obtained such that the concrete will have the proper friction head loss properties while in the pipeline and coherent mounding behavior when discharged from the pipeline. Another assumption is that friction values for a given mix design can be determined by laboratory tests prior to an operation so that the pipe can be sized properly. These and other assumptions will be discussed in more detail. Validation of these items is considered to be a low risk research effort.

Advancing the technology to place concrete on the seafloor will considerably expand the Navy's capabilities to perform ocean engineering tasks. Several potential applications and the benefits of this new capability are discussed in the next section.

APPLICATIONS

Potential applications for placing concrete in the deep ocean are basically in three areas: in situ construction of anchors and foundations for fixed ocean facilities, in situ hardening of structures or objects on the seafloor, and containment of hazardous or polluting substances for environmental protection. Such applications would require portland cement concrete to be placed underwater in quantities of hundreds and thousands of cubic yards in water depths as great as 20,000 feet.

The capability to construct and install very large anchors and large seafloor foundations and structures in deep water has been identified as a near and mid-range requirement in a recent study of capabilities needed by the Navy for fixed ocean facilities (Ref 1). A military task which requires this technology can arise quickly. Conversely, if the technology is available and known to planners and designers, they may conceive and implement tasks which otherwise they may dismiss as too advanced.

The hardening and containment applications also may arise at any time. Thus, there is a need to be ready with the appropriate methods and means to minimize the consequences or problems that could develop. The capability of concrete placement is a "tool" which should be available.

In Situ Seafloor Construction

Future requirements have been identified for massive deep ocean anchors with holding capacities on the order of 2 to 20 million pounds for fixed ocean facilities (Ref 1 and 2). The most practical way to provide such large holding capacities in most deep ocean seafloors is to use very large deadweight anchors. In certain hard seafloors, the large anchor forces may be best provided by clusters of piles drilled into the bottom and connected together with large pile caps (Ref 2).

A 20 million-lb capacity deadweight concrete anchor would have a submerged weight of about 40 million pounds and thus be about 160 ft in diameter by 20 ft thick. This is comparable to the quantity of concrete in a large building mat foundation or a bridge pier but is small compared to a concrete offshore oil platform or a deadweight anchorage for a suspension bridge cable.

Methods do not presently exist for the deployment of the large deadweight anchors since the loads are beyond the capacity of existing heavy lift equipment. A number of drill ships exist that can lift about one million pounds in deep water. A few crane barges are available rated at six million pounds for surface or shallow water lifts. One ship in the world, the Glomar Explorer, has had the capability to lift a design load of about eight million pounds from a depth of 17,000 ft, but is currently being converted to an ocean mining ship. Two or three other recently developed mining ships have deep water lift capacities greater than the drill ships' but less than the Glomar Explorer's.

Outfitting the barges or mining ships or re-outfitting the Explorer for multi-million pound anchor deployment would be very expensive, as discussed in the cost estimate section below.

A method has been proposed for free-fall emplacement of large deadweight anchors in deep water where seafloor site conditions are favorable. This method is designed for applications in which precise positioning is not critical, such as a single point deep ocean mooring but is not appropriate for those cases where more precise positioning is important, for example, placing an object at a predetermined seafloor position or placing objects in close proximity to each other. Free-falling is not an appropriate emplacement technique for all sites at which very large deadweight anchors would be used but only for those sites with a soft seafloor at a fairly flat slope (Ref 2).

An alternative to lowering or free-falling a massive anchor is to combine pre-fabrication and in situ methods as commonly practiced for steel and concrete construction. A shell would be free-fallen or lowered to the seafloor using existing lift capability and then filled with a heavy material emplaced from the surface platform (Figure 1). Concrete is a prime candidate for the heavy material. Concrete normally weighs about 150 lb/cu ft; suitable mixes can readily be produced in weights up to about 200 lb/cu ft by using iron ore aggregates. This compares with high density oilwell slurries which weigh up to about 135 lb/cu ft when weighted with barite and to 160 lb/cu ft with magnetite. The shell, made of concrete or other materials, would be 100 feet or more in diameter. The mooring connection and other hardware would be built into the shell as needed.

Hardening

If an object of strategic significance is lost on the seafloor, a decision to salvage the object could be expensive, particularly if the object is lost in deep water and is very large, such as a ship or submarine that is too heavy to lift in toto. A recovery operation comparable to the Glomar Explorer's retrieval of a portion of a 2,800-ton submarine from 17,000 ft would cost perhaps on the order of $100 million. This is below the reported $400 million cost of the original Glomar Explorer expedition because the vessel and the technology now exist.

Concrete placement makes another option available for consideration. Rather than salvaging the object it is encapsulated in place on the seafloor by covering it with concrete (Figure 2). The purpose is to sequester the object in such a way as to deny observation, access or removal of portions of it by others. The operational cost for encasing a ship-sized object is estimated to be about $2 million. A cost breakdown is shown in a following section. This is a substantial savings compared to a recovery operation.

For smaller-sized objects such as an airplane or weapon system, in situ hardening may also have application in those cases where concrete encasement is faster and costs less than recovery. The retrieval of the

15-ton F-14 TOMCAT from 1,900-ft water depth 100 miles off Scotland in 1976 reportedly required about two months, involved seven vessels and cost about $2 million (Ref 3).

Another potential application of hardening is the stabilization of ocean cables and pipelines on firm seafloors in deep water. The purpose is to prevent accidental damage which is caused mostly by trawlers and, importantly, to preclude purposeful damage. At the present time, cables and pipes are protected by burial in those seabottoms soft enough to be trenched. In bottoms not suitable for trenching other protective methods are needed. In some cases, pre-cast concrete covers have been placed over seafloor cables to stabilize them on a firm bottom (Ref 4). A study is currently underway in Norway on in situ concreting of underwater pipelines (Ref 5).

Containment of Hazardous Substances

Another potential application of placing concrete on the seafloor is to cover or contain hazardous substances for the purpose of isolating them from the environment. Again, this is an alternative to recovery. A hazardous material incident could involve radioactive materials from a nuclear power source or weapon system. Another example is containment of hazardous materials dumped in the ocean in the past and presenting a potential problem in the present. Biochemical agents have been dumped off the U.S. East Coast and radioactive wastes from earlier military and civilian developments have been placed on the seafloor in the Pacific Ocean near San Francisco and the Atlantic Ocean off Maryland. Leakage problems if they arose could be resolved in many instances by encasement in concrete.

BACKGROUND

Prior Work

The Civil Engineering Laboratory conducted a literature survey in 1966 on state-of-the-art methods of subaqueous concrete placement. The report concluded that, for general use, the most practical methods to consider for adaptation to placing concrete in forms in the deep ocean were the pumping method and the preplaced aggregate method; bucket placement would be practical for small quantities. Also a concept was proposed adapting an existing cargo-type submarine for use as an underwater concreting plant. The submarine has the advantage of avoiding the air/sea interface motion problems and could be used covertly. It would be limited by size and strength of the pressure hull to placing small quantities of concrete at depths less than about 1,000 feet, unless an expensive special hull were built (Ref 6).

In 1971 Santa Fe-Pomeroy performed a study for the Civil Engineering Laboratory of construction methods for large undersea structures. The emphasis was on documenting the then existing capability of the construction industry to fabricate large concrete spheres and cylinders and to emplace them on the ocean floor. Potential technology for extending construction capability to 3,000 ft depths was also considered including in situ construction methods in which concrete is mixed on a surface vessel and transported to the seafloor by bucket and pipeline methods. For the complex type of structures studied prefabrication or modular construction with in situ grouting was considered most promising (Ref 7).

Recently, a study was performed by Halliburton Services for the Civil Engineering Laboratory on conceptual methods for placing concrete at deep water depths (Ref 8). Five concepts were presented. The present authors consider that one of the concepts, called "Pumped Tremie Method (Closed System)," has the potential of being a versatile system for placing concrete at shallow or deep depths with or without the use of forms. It is this concept which is reported herein after being advanced by studying the technical and operational aspects of the placement method.

State-of-the-Art Methods

A number of state-of-the-art methods exist for transporting concrete and similar materials by pipeline and for placing them underwater. These methods are discussed briefly.

Tremie Method. The construction industry regularly places large quantities of concrete underwater by tremie methods at depths of tens of feet to one or two hundred feet in protected waters for bridge piers and other waterfront type structures (Ref 9). Concrete falls by gravity through open pipes and is placed in forms or confined spaces. Flow rate is controlled by depth of burial of the lower end of the tremie in the concrete. Good quality concrete is regularly produced using established mix designs and operating procedures. Maximum depth of placement underwater to date is about 400 feet. Major limitations on going deeper are difficulties in starting the flow and maintaining control of the flow without runaway of the high slump concrete in the typically 12-in. or greater diameter pipe. Special approaches have been tried such as foot valves and pipe-within-pipe methods but these do not promise an order-of-magnitude increase in depth capability without considerable development of relatively complex methods. Also, the total weight of tremie pipes filled with concrete becomes very great with increasing depths.

Bucket Method. Large and small quantities of concrete have been successfully placed underwater by covered, bottom-opening buckets of up to several cubic yard capacity. Bucket placement is used primarily in relatively shallow water although depth is restricted more by operational considerations than by technical limitations. Stiffer concrete with larger aggregate (up to several inches diameter) can be placed by bucket

than by tremie. Specially designed bucket methods have been proposed that would be suitable for placing small but not large quantities of concrete in the deep ocean (Ref 7 and 8).

Concrete Pumping. Pumping concrete through pipelines of 2-in. to 8-in. diameter is a well-established practice on land for horizontal distances of 1,000 ft or greater and vertical distances of several hundred feet upward (Ref 10). Reliable equipment and experienced operators are available; mix design is well known to produce pumpable, good quality concrete. Difficulties that do occur are usually due to not following standard procedures, for example, attempting to save costs by using borderline materials, equipment or practices, or are due to operational delays.

Pumping downhill is often troublesome and is not frequently done. However, in some instances, concrete has been pumped down for placement underwater in water depths to about 200 feet. In pumping downhill it is important to avoid the formation of air pockets and voids in the pipeline. Both large air bubbles and voids can disrupt the flow and cause segregation of the mix which in turn causes blockage of the pipeline. A bleed valve at the high point of the pipeline is used to vent air during initial filling of the pipe with concrete, after which the valve is closed. Flow is then maintained under continuous positive pressure to prevent formation of voids.

Pumping methods offer the potential for an order-of-magnitude increase in water depths at which concrete can be placed provided that: (1) means are developed to maintain a positive pressure continuously throughout the fully-filled pipe and to control the flow rate, and (2) the characteristics of the fresh concrete required for the controlled flow in the pipeline can be made compatible with the concrete characteristics required after the concrete is discharged from the pipe at the seafloor. The placement method discussed in this report uses a closed system, pumping approach.

Pumping Grouts and Mortars. Grout is a mixture of either cement and water (neat cement grout) or cement, water, and sand (sand grout), both having a fluid consistency. Mortar is a mixture of cement, water, and sand usually of a stiffer consistency than grout. Grouts and mortars often contain admixtures to control setting, minimize bleeding, or otherwise affect the material characteristics. Grouts and many mortars are readily pumped.

Grouts are regularly pumped through small (e.g., 1-in.) diameter pipes and placed in confined spaces for many construction applications, such as repair of concrete, encasement of post-tensioning tendons, and construction of water cut-off curtains under dams.

Grout pumping is also used for underwater concreting by the pre-placed aggregate method by which large quantities of concrete have been successfully placed to depths greater than 100 feet for construction of large bridge piers and other purposes. The coarse aggregate is placed in forms and then intruded with a fluid grout through pre-positioned grout pipes. This method might be adapted to deep ocean placement but probably would require a complex operation since separate placement

systems would be needed for the forms, the aggregate and the grout. The method would be limited to applications using forms or other confined space.

Large quantities of grout, on the order of 10,000 cu yd, have been placed under offshore gravity-type structures located in water depths to 450 feet. The purpose is to provide uniform bearing on the seafloor and to minimize settlement, especially differential settlement. Grouts used for this purpose develop low strengths and are placed in confined chambers.

Probably the largest deep placement operation was one in which more than 1,300,000 cu yd of 3/8-in. maximum size aggregate mortar were pumped downward about 1,000 feet into a large water-filled cavity under a dam (Ref 8). The purpose was to fill the enclosed void. Structural grade concrete was not required.

Cementing Oil Wells. Sophisticated above-ground and down-hole equipment, materials and procedures have been developed to cement oil wells to depths of 20,000 feet or more under conditions of high pressure and high temperature (Ref 11). Practices are limited to placing cement slurries in confined holes using the back pressure of the drilling fluid to control flow. Concrete is not used. Cement slurries are typically water, cement and various specialized admixtures. For certain purposes, such as increasing the unit weight of the grout, fine sand is sometimes used. The maximum sand grain size that can be accommodated by pumps and downhole equipment is about 1/8 in. diameter. Sand, when used, is typically smaller than no. 20 size; i.e., about 1/30-in. in diameter.

Well cementing methods have been adapted to some offshore platform construction: grouting platform pin-piles to the seafloor and grouting-in anchor piles. On one occasion a number of bell-bottomed reinforced concrete piles of 3-1/2-ft diameter belled out to 9- to 15-ft diameter at the bottom end were constructed in a total depth of about 500 feet. A grout with maximum sand size of 1/30 of an inch was pumped into a drilled hole (which contained the steel reinforcing cage) to displace a weighted mud slurry.

Combined theoretical and empirical methods are used to predict the flow behavior in a pipeline of cement slurry treated as a non-Newtonian fluid. Flow calculations utilize experimentally determined coefficients related to slurry viscosity in laminar flow. This method is not directly applicable to plug flow of concrete in a pipe.

The major aspect of construction grouting and oil well cementing technology that is adaptable to deep ocean concrete placement is the control of material properties, particularly prevention of water loss from grouts and slurries under high pressures and pressure differentials. These properties are controlled primarily by careful selection of materials, control of mix proportions, control of procedures and use of specialized admixtures. Pumps and other equipment for grouting and cementing are not adaptable for concreting.

Mine Construction. Concrete for shaft and tunnel lining and other underground construction has been transported to the deep depths by dropping the freshly mixed concrete down long vertical pipes. Copper mines in the U.S. and gold mines in South Africa have shafts that are

several thousand feet deep. The concrete segregates during the fall and is usually remixed at the bottom before being placed. This method is not applicable to underwater placement.

Slurry Transport. Particulate matter such as coal is transported long distances in "slurry pipelines." Similarly, spoil from hydraulic dredges and many materials in processing plants are transported in pipelines by two-phase flow with the suspended solid particles propelled by the drag forces of the faster moving water or other fluid. Usually turbulent flow is maintained to prevent particles from settling out. This technology is not applicable to pipeline transport of concrete.

SYSTEM DESCRIPTION

Overall Configuration

A representative arrangement for a deep ocean concreting operation is shown in Figure 2. The surface platform is positioned at the site with the pipeline deployed for concrete encasement of objects on the seafloor. The pipe handling mast is located amidships over a center well. Pipe is stored horizontally on the deck. The concrete batch plant, mixer and pump and the concrete materials storage bins are located on one or more decks; for large jobs additional materials storage would be on a barge alongside.

Concreting System

The components of the concreting system are shown schematically in Figures 3 and 4. The materials storage, conveying and batching equipment, and the concrete mixer and pump are conventional concreting equipment. The pipeline consists of standard oilwell tubular goods. The pressure equalizer, the concreting head, and the seafloor discharge device are not off-the-shelf items and are specifically built for deep ocean concreting operations.

Materials Storage and Handling. The concreting materials are the cement, sand and gravel aggregates, water and admixtures. A typical concrete for use in the ocean weighs about 150 pounds per cubic foot or 2 tons per cubic yard. The aggregates make up more than 75 percent of this weight, the cement about 16 percent, water about 8 percent, and the admixtures a fraction of a percent. The bulk weight of the stored aggregates is roughly 100 pounds per cubic foot and of cement 75 pounds per cubic foot (aerated bulk density after being conveyed pneumatically) so that about 4,600 cubic feet of storage volume are required for each 100 cubic yards of concrete to be placed. Weight and volume storage requirements for materials to produce various quantities of concrete are shown in Table 1.

Industry has developed bulk materials storage and handling methods including portable and relocatable systems for temporary applications that are suitable for barge or shipboard use.

Cement is best stored and transported in bulk in closed tanks, commonly available in sizes up to 3,000 cubic feet. Cement is readily conveyed pneumatically through standardized hoses and pipes at 20 to 40 psi air pressure. Offshore supply boats are characteristically outfitted with several pressurized tanks of up to 1,000 cubic feet each, and associated air compressors and piping; additional tanks can be loaded on the deck. A large drill ship will have 10,000 to 25,000 cu ft of bulk cement storage capacity.

About three-fourths of the required materials storage weight and space capacity is needed for the aggregates of which there will normally be at least three sizes: a sand and two sizes of coarse aggregate. Established methods for waterborne transport and handling of heavy materials will be used. Aggregates will be stored in low rise bins in holds or on deck and moved horizontally and vertically by conveyer belts and bucket elevators.

The proposed concreting method requires careful control of the concrete properties which depends, in turn, on close control of the water content and the salt content of the aggregate. Therefore, covered storage is preferred, especially for the sand, to protect it against wetting by waves and spray.

Water tanks and pumps are standard items. Water must be clean and not contaminated with oil or other substances. For applications requiring large amounts of concrete, the use of seawater as the concrete mix water would preclude the need for large water tanks and could be used with sufficient prior testing. However, fresh water is usually preferred as a mix water since the properties of the fresh concrete are usually easier to control. A large drill ship will have 45,000 to 85,000 cu ft water storage capacity.

Batching and Mixing Equipment. A portable central-mix concrete plant would be set up on the deck of the ocean platform. The plant should have an automatic positive batching and mixing system with operator override so that all operations, particularly mix time and discharge from the mixer, are under full control of the operator. Cement and aggregates would be batched by weight, water by weight or volume so long as the method is accurate and dependable and continuously adjusts the amount of added water to automatically compensate for variation in the water content of the sand. Admixtures will be precisely dispensed either wet or dry in a manner to assure uniform distribution throughout the mix. The concrete will need to be well mixed; this may require a longer than usual mixing time. The mixer will discharge into a holding hopper of the pump.

One of the most important attributes of the overall material handling and concrete batching and mixing system is the capability to produce a uniform concrete, particularly in terms of density and slump, under varying rates of production.

Concrete Pumping and Transporting Equipment. The concrete pump should have a high pressure rating (say 1,000 psi) and a large capacity (say 100 cubic yards per hour), but still be capable of operating efficiently in its low capacity range.

Concrete should be delivered to the pipeline smoothly and continuously and relatively free of pressure pulsations. A two-cylinder oil-hydraulic pump with a long stroke operating well below its maximum capacity can deliver concrete at a fairly constant pressure throughout a stroke and with a minimum of dead time between strokes. To further smooth out the pressure pulse, the pump can discharge into a pressure equalizing chamber and it, in turn, into the concreting head.

The concreting head (Figure 3) provides a tightly sealed connection to the top end of the vertical pipeline and also provides a means for venting air, for inserting cleaning plugs, and for using a wire line, while maintaining pressure and flow of the concrete through the pipeline.

The vertical pipeline for transporting the concrete to the seafloor is discussed in a later section.

Seafloor Discharge Device. The function of the seafloor discharge system is to deliver the concrete underwater at the desired location in a coherent mass. Once flow has started, the concrete exit point is kept buried in the concrete already placed so that concrete is added to the interior of the mass. The mound grows by expansion in size from within rather than by addition of concrete on the surface of the mound. This procedure produces a compact mound with a minimum of washing out of cement or intermingling of concrete and seawater. The shape of the growing concrete mound is influenced by the properties of the concrete (such as slump), the discharge rate, the velocity of flow, and the depth of burial of the discharge point. The proposed 2- to 3-in. slump concrete will stand at a fairly steep angle. The velocity is reduced in the expansion chamber portion of the discharge device. The maximum depth of burial of the discharge point is maintained at 5 to 7 feet. (If the discharge pipe is buried too deeply, the concrete spreads out in a flat shape; if not buried deeply enough, the concrete wells up around the pipe and spills out on the surface.)

A concept for a discharge device is shown in Figure 4. The velocity dissipation chamber has an increasing taper to prevent blockage by arching of aggregates. The tank-like "float" rides on top of the concrete once the mound has grown to several feet in height and thus maintains the discharge point at a fixed depth of burial as the mound continues to grow. The telescoping slip joint acts as a heave control device. The joint should accommodate up to 15 feet of vertical movement to decouple the discharge device from the pipeline.

Auxiliary Equipment for Concreting. A small field laboratory should be provided in order to make tests of materials and fresh concrete for control purposes.

Back-Up Equipment. System reliability is important for an at-sea operation. For a large job back-up equipment, particularly a concrete pump, should be provided.

Pipe and Pipe Handling

The pipeline from the surface platform to the seafloor would probably consist of oilwell tubular goods, either "tubing" or "drill pipe," depending on specific availability. Oilwell pipe is furnished in 30-foot lengths with threaded joints; pipe is manufactured in various sizes and material grades to American Petroleum Institute standards for size, shape, joint configuration, and tensile, burst and collapse strength.

For the proposed concreting system, pipe in the 3-1/2 to 5-in. size range will likely provide the desired combination of flow capacity and friction head loss. Flush joints of constant internal diameter will be used in order to minimize disturbance to flow.

The pipe handling system consists of a conventional oilwell mast, drawworks, other hoisting and joint make-up equipment and power supply. If a floating drill ship or barge is chosen as the platform, this equipment will already be in place. If a special barge is outfitted, then a portable rig would be rented and installed on the barge. Either a workover rig or a small drilling rig with a 250,000-lb hook capacity is adequate to support a submerged weight of up to 10,000 ft of 3- to 4-in. ID pipe filled with concrete, as shown in Table 2. The pipe handling system may need to have some modifications such as provision of lateral guides on the mast for the traveling block.

The pipe will be stored horizontally in stacks on the deck. As an example, 4-1/2 in. tubing in 30-ft lengths stacked in several layers requires about 150 feet of deck space for each 1,000 feet of pipe, which has a total weight of about 14,000 pounds and thus a deck loading of 90 pounds per square foot. Some rigs can handle 60-ft doubles (two 30-ft lengths already joined) or 90-ft triples. The longer stands permit faster placing and retrieving of pipe. For example, both the Glomar Challenger and the CALDRILL can deploy about 14 stands per hour. The Challenger, using 90-ft lengths, requires about 4 hours to place 5,000 ft of pipe; the CALDRILL, using 30-ft lengths, needs about 12 hours. However, longer stands require longer clear deck space for storage and extra mast height with its additional weight and increased operational difficulties on a rolling and heaving platform.

Pipeline of the type that is normally used for pumping concrete on land is not suitable for a long vertical line: it lacks tensile strength and suitable joints; no practical deployment system exists.

Flexible pipe (hose) is often used for pumping concrete. However, hose is more subject to blockage than "slickline"--rigid steel pipe--and is otherwise less suitable for vertical transport of concrete. Also, reinforced hose with adequate tensile and burst strengths is considerably more expensive for two reasons: (1) it costs more per lineal foot than steel pipe, and (2) it is not readily available off-the-shelf in long lengths and likely would need to be specifically manufactured along with its deployment system, thus incurring substantial capital investment.

Marine and Ocean Engineering Systems

Marine and ocean engineering systems include surface platforms, positioning systems, operations monitoring systems, and lifting/lowering systems.

Surface Platforms. Ocean platforms, such as drill ships, work boats and barges, are suitable for the concrete placement operation. A drill ship is probably the best suited vessel for the task because it already has the necessary marine operations systems, most of the ocean engineering systems, and the pipe and pipe handling systems, all in place and functioning in a demonstrated manner by crews experienced in working together. Drill ships typically have some oil well cementing capability but this is too limited for our purposes. The main items to be added to the drill ship are the materials, the materials storage and handling equipment, the concreting equipment, and the concreting personnel.

For a small operation using a small drill ship such as a deep ocean coring ship, the concreting equipment and materials would be placed on a barge alongside the drill ship. Concrete would be pumped from the barge to the drill ship and then (by a second pump on the drill ship) down the pipeline. A small drill ship suitable for placing several hundreds of cubic yards of concrete to 5,000 ft or greater depths may be leased for about $7,000 per day including marine and drilling crews working a 24-hour day, and a barge for $2,000 per day.

On a large job using a large drill ship there would be space on board for the concreting equipment and some materials storage. A barge alongside would provide major materials storage. A shuttle barge would resupply materials as needed. Representative costs are $30,000/day for a drill ship, $2,000/day for a barge, and $5,000/day for a tugboat and shuttle barge combination.

Many drill ships that can moor in 600-foot water depths are located around the world. Also some drill ships can moor in water depths to 2,000 feet; the number of these vessels is increasing all the time. Only a few drill ships can keep station in deep water. Thus a major limiting factor in adapting drill ships for deep ocean concreting is the station-keeping capability in deep water of available vessels. For depths less than 2,000 feet or so, most drill ships are outfitted to moor with anchors. Some drill ships are equipped with dynamic positioning systems for operating in depths to 3,000 feet, but could maintain station in much deeper water. Dynamic positioning systems are typically sophisticated and expensive although less expensive systems exist. For example, a small seafloor coring ship, the CALDRILL, works to 6,000-ft water depths using four Harbormasters manually controlled to position the ship relative to a taut wire reference.

Another approach is to use an ocean-going workboat such as NAVFAC's SEACON. This ocean construction barge has established marine operations systems, including dynamic positioning, and ocean engineering systems, as well as a center well and considerable deck space. Pipe and a handling system, such as a portable oil well rig would be added as would the concreting equipment.

For an operation where a drill ship or work ship is not available in a timely manner, a barge or other available vessel could be outfitted for the specific operation with (1) a leased oil well rig including pipe, crew and accessories, (2) a leased portable concreting plant and materials storage and handling systems, (3) mooring, positioning and other systems to suit the given operation, and (4) crew accommodations and work space.

This approach has the disadvantage of having to provide and shakedown the marine and ocean systems as well as the pipe, concreting and materials systems. Advantages are that in some instances, perhaps in a remote area, it would be faster, or more cost effective, to use a locally available platform.

Positioning Systems and Operations Monitoring Systems. Both position determination and position control systems are required at the surface and at the seafloor for the horizontal and vertical directions. The positioning and monitoring systems used for a given concreting operation will depend on the specific needs of that operation and on the capabilities of the drill ship or other surface vessel.

The position determination system furnishes information on the horizontal and vertical location of three objects: the surface platform, the sub-sea object, and the lower end of the pipe string. These objects are located relative to each other and to some frame of reference such as geographic coordinates or a nearby taut buoy. Surface position determination systems include traditional navigational methods as well as more precise location systems such as satellite navigation, ship's radar, electronic distance measurement systems and horizontal angle measurement systems such as theodolites and lasers. Water column and seafloor navigation and position determination systems include short and long baseline acoustic transponder systems, load mounted sonar and TV, taut wireline to seafloor, and pipeline inclination measurement systems. Vertical position may be determined by fathometer, load mounted sonic altimeter, and measurement of the length of pipe or wireline inside the pipe. Television is useful for target acquisition and initial approach to the seafloor as well as for post-operation observations, but will not be useable during concreting due to turbidity.

The primary function of the position control system is to place and maintain the discharge end of the pipeline at the desired horizontal and vertical position at the seafloor relative to the target location. Position will be controlled by a combination of maneuvering and station keeping of the surface ship for the gross position control, and the use of guidance devices (guidelines, posts, funnels, and cones) and subsea motive systems (attached near the lower end of the pipeline) for the local fine position control at the seafloor. Horizontal surface position is controlled by single or multiple point mooring systems in water depths to 2,000 feet or so, or by dynamic positioning to maintain the vessel at the desired surface position. Propeller and jet thrusters have been proposed for the attachment to the lower portion of a pipe string for its horizontal position control near the seafloor. These methods have been found to be unnecessary in many cases in actual

experience. Well hole re-entry is usually performed by maneuvering the surface vessel and, once sonar or TV monitoring confirms alignment, stabbing the lower end of the pipeline into the seafloor guide funnel. Assembly of seafloor well heads is usually performed by maneuvering the surface vessel and the use of taut guidelines and guideposts.

In the present case, a multi-point mooring system with taut lines to shipboard winches, as shown in Figure 2, can control the location of the bottom end of the pipeline for accurate positioning and stabilization against random motions due to surface vessel excitation (Ref 12). This type of system has performed successfully to 3,000-ft water depths and is considered to be adaptable to deeper water.

Successful vertical position control (heave control) methods for pipe strings vary from manual adjustment to telescoping joints (bumper subs; riser slip joints) to various passive and active tensioners for guidelines and riser pipes and heave compensators in the pipestring hoisting system between the hook and the traveling block or at the crown block. Stabilized platforms such as column stabilized semi-submersibles are an appropriate solution.

For concrete placing by pipeline, vertical motion control is primarily needed to keep the lower end of the pipe buried in the concrete during discharge. The required vertical motion compensation can be obtained by the use of telescoping slip joints in the pipestring near the bottom just above the seafloor discharge device. Either specifically built slip joints or commercially available bumper subs can be used. For concreting with a 3-inch ID pipeline, it is probably more economical to use one or more standard bumper subs (each with a 5-foot stroke) in series as is common practice in oil well drilling. For larger diameter pipelines, standard bumper subs are special order items so telescoping joints would probably be more economical to build than bumper subs.

TECHNICAL CONSIDERATIONS

General Approach

For successful in situ seafloor concreting the key procedures are transporting the concrete vertically downward and discharging the fresh concrete at the seafloor. Thus, techniques are needed to control the flow of concrete through a long vertical pipeline without blockage and without runaway of the flow rate, and to control the discharge behavior of the fresh concrete at the seafloor. The concrete delivered to the seafloor should have the desired characteristics (consistency, time to initial set, strength when hardened, etc.) and be delivered in desired quantities in a minimum length of time. The major factors of interest that interact with each other are listed in Table 3. The most important of these factors are probably the purpose of the placement, the water depth and the total quantity of concrete required.

The rigid pipeline, suspended from the surface platform, will be closed to atmospheric pressure at the upper end. Fresh concrete is pumped into the vertical pipe under positive pressure. The concrete flows, primarily due to the force of gravity, down the pipe and is discharged at the seafloor.

The most serious cause of pipeline blockage is segregation of the concrete constituents, particularly "bleeding" of the water. To prevent segregation as the concrete travels through the pipe, it is important that there be no air pockets in the line and that there be no voids from the material separating. Also, it is important to maintain plug flow.

At the beginning of a pour, air in the pipeline system should be vented at the concreting head or other high point in the line. Voids in the concrete can be prevented by keeping the pipe completely full of concrete and under positive pressure throughout its entire length. Once concrete flow has begun, it should continue uninterruptedly. Thus, there is a need for a backlog of material and backup mixing and pumping capability.

The means for preventing runaway velocity of the flow is to use a concrete mixture that has friction head loss characteristics which cause terminal velocity of flow, for a given pipe diameter, within a reasonable range, probably about six to ten ft/sec. Higher velocities lead to laminar or turbulent flow which could cause segregation. A valve or throttle will not be used at the seafloor to control the flow velocity. The use of a valve or throttle is specifically avoided since the high pressure differential across a throttle or a partially closed valve may lead to blockage and thus seriously diminish the reliability of the system.

Once the concrete discharge has started at the seafloor, the lower end of the pipe must be kept buried in the already emplaced concrete to prevent mixing with seawater and the cement washing out of the concrete. For most applications, where concrete is emplaced without confinement by forms or other means, it will be desirable for the concrete to build up into a mound of well consolidated material with fairly steep side slopes (say about one vertical for each two horizontal). Therefore the concrete will need a fairly stiff consistency, for example a slump of about two or three inches.

As the concrete descends down the long pipeline, pressure can increase to thousands of pounds per square inch in deep water. This change in pressure may affect the concrete characteristics, for example, cause a reduction of slump and thus increased friction.

State-of-the-art knowledge is available for placing concrete underwater to depths of several hundred feet, and for pumping concrete through a pipe at pressure heads up to about 1,000 psi and velocities of flow of two or three feet per second. For the proposed application concrete will be flowing through a pipe at much higher pressures (several thousand psi) and higher velocities (up to about 10 ft/sec). The concrete will have a much stiffer consistency (about 2 to 3 in. slump) than that usually placed underwater (about 6 to 7 in. slump).

A major engineering assumption has been made: that available state-of-the-art knowledge on concrete mix designs can be adapted and extended for use in the new environment. Such an assumption needs to be verified by laboratory tests on concrete mixtures that will simultaneously meet the requirements of: (1) the flow of concrete through pipelines at the higher pressures and velocities and (2) the behavior of the stiff concrete discharged underwater.

Flow of Concrete in a Pipeline

The flow of concrete through a pipeline is usually described as "plug flow" in which the main mass of the concrete slides along on a thin lubricating film of water, cement and very fine sand on the inside wall of the pipe. The following discussion of concrete flow behavior and resistance in a pipe is based on work reported in References 13 through 16 and summarized in References 17 and 18.

The plug of concrete consists of the particles of cement, sand and coarse aggregate, and a water phase which occupies the continuous interparticle void space. As shown in Figure 5 the flow velocity is essentially constant across the plug and drops rapidly across the lubricating film to zero at the pipe wall. Thus in a straight pipe of constant diameter there are no internal shear stresses within the plug. The resistance to flow is considered to be due to the friction between the peripheral surface of the plug and the inside surface of the pipe wall, and to the internal shear force within the lubricating layer. At a change in pipe direction or diameter, resistance to flow changes since the solid particles within the plug move relative to each other and develop internal shearing forces similar to those in a fluid in laminar or turbulent flow. For mild bends and tapers whose total length is small compared to the overall length of the pipe, the contribution to resistance due to internal shear in bends and tapers is a small percentage of the total resistance.

If flow velocity increases above about 7 to 10 ft/sec (depending on the pipe diameter and on the individual mix) the central core of the concrete tends to move faster than the concrete closer to the pipe wall. The flow thus assumes a laminar or quasi-laminar flow profile with internal shear stresses. The behavior of concrete in this flow regime is not well known, but a tendency for the coarse aggregate to accumulate in the central core can be postulated. Such a moderate segregation by aggregate size could be aggravated by the cumulative effect of long distances to the point of concentrating the coarse aggregate into rock pockets which could then cause sudden blockages by arching. Since this is an unknown regime, velocities higher than about 10 ft/sec should be avoided until this problem can be studied.

Effect of Saturation on Flow Resistance

The resistance due to friction of the solid particles in contact with the pipe wall is strongly affected by whether or not the concrete is saturated. In the saturated state the water completely fills the interparticle void volume. In fact, it is necessary to have sufficient water to overfill the voids in the dry material. Thus, the water separates the solid particles and the intergranular pressure between particles is negligibly small, as is the normal force of the particles against the pipe wall. In this saturated state, the concrete is forced through the pipe by the hydraulic pressure in the water. The radial pressure against the pipe wall is nearly equal to the longitudinal pressure since it is due almost entirely to the hydraulic pressure of the water and little to the solid particle pressure.

Laboratory and field tests (Ref 13-18) have shown that for a saturated concrete flowing through a straight pipe of constant cross section in plug flow the total resistance to flow is (approximately) directly proportional to the length of pipe and to the velocity of flow, and inversely proportional to the pipe diameter. Resistance is essentially independent of radial pressure and total pressure, for the range of pressures tested to date (up to about 1,000 psi), provided that the pressure does not change the characteristics of the concrete mix, for example, by decreasing the interparticle void volume by compressing entrapped air or forcing water into porous aggregates.

It is assumed that the above stated relationships between resistance, length, diameter and pressure can be extended to the pressure environments of interest in the deep ocean (8,900 psi at 20,000 ft). However, this must be verified by laboratory tests.

Different concrete mixes will have different characteristics of flow resistance; that is, the above linear relationships are relative to a specific mix. If the mix changes, then the resistance properties may also change. The effect of mix characteristics on friction is discussed in a later section.

When the concrete is not saturated the water does not completely fill the interparticle void volume, the particles come in contact with each other, an intergranular pressure develops, the ratio between the axial and radial pressures changes, and the contact pressure between the solid particles and the pipe wall increases dramatically. The resistance to flow is much greater for unsaturated than for saturated concrete. Additionally, unsaturated concrete usually exhibits dilatancy; any movement of solid particles relative to one another tends to cause an increase in the total interparticle void volume, and thus, if the volume increase is constrained, an even greater intergranular stress and wall friction are developed.

The resistance to flow of concrete in the unsaturated state is not linearly proportional to pipe length, but is a function of the radial pressure; also the relationship between the radial pressure and axial pressure changes with change in axial pressure.

The difference in flow resistance between a given mix in a saturated state and the same mix in an unsaturated state is great. The unsaturated mix can develop the same amount of total resistance in a few feet of pipe length as that developed in several hundred feet of pipe length in saturated flow. Additionally, unsaturated concrete may be subject to bridging and arching of the aggregates across the diameter of the pipe as discussed below.

<u>In practice, then, the concrete mix must be saturated</u>. If it becomes unsaturated, blockage may occur almost immediately. A common cause of change from saturated to unsaturated is bleeding of the water. Bleeding is prevented by providing a mix that is "plastic" and "cohesive," by avoiding high pressure differentials (such as an abrupt change in pipe diameter), and by avoiding large discontinuities (such as air bubbles and voids) in the water phase.

Effect of Concrete Mixtures on Flow Resistance

The characteristics of the materials and their proportions in the concrete mixture affect the flow resistance in several ways. The two most important characteristics of the mixture are the inherent resistance of the mix to bleeding and the magnitude of the flow resistance when the mix is saturated.

To provide a cohesive mix that will not bleed easily the mix is proportioned by the method of minimizing the total interparticle void volume between the solid particles of cement and aggregates. The void space is continuous but the individual channels that remain for water passage are extremely small and intricately interconnected. Thus when the mix is saturated with water, hydrostatic pressure can be transmitted via the water phase yet the small diameter, high specific-surface-area interstices limit the flow of water through the mix.

Mix design is by careful gradation of the successively smaller sizes of aggregate and cement so that the voids between larger solid particles are filled with smaller particles and the voids between them with smaller still. This provides small tortuous paths for the water to migrate through the aggregates. In this condition, hydraulic pressure moves the mass of concrete down the pipe rather than just the water through the interstices of the solids.

Three ways in which the mix proportions affect resistance to flow of saturated concrete are shown qualitatively in Figures 6, 7 and 8. Quantitative information depends on the specific mix and size of pipe. The information presented is based on laboratory tests in which the pressure required to pump concrete was measured while the following individual factors were varied: (1) cement content, (2) size, shape and percentage of coarse aggregate, (3) amount and gradation of fine aggregate, (4) consistency of mix, and (5) pipe diameter and length (Ref 16).

The saturated state resistance to flow is strongly affected by the amount and fineness of the fine material, particularly the total amount of very fine material; i.e., the cement and fine aggregate passing the number 200 sieve.

In Figure 6 it is seen that the resistance is a minimum at a certain amount of total fines per cubic yard indicated by point "A." As the amount of fines is decreased, the resistance increases gradually until at a certain minimum amount of fines indicated by point "B" blockage of the pipe occurs abruptly due to arching where the resistance suddenly increases to a very large value. On the other hand, if the amount of fines is increased past point "A," the resistance increases smoothly to a higher value than at "A" but without blocking the pipeline.

Thus the control of terminal velocity of concrete traveling down the pipeline is best achieved by adjusting the total amount of "fine fines" in the mix so that the system is operating in a resistance range in the vicinity of point "C." The velocity of flow can then be further controlled by varying the pump pressure.

The influence of the amount and size of coarse aggregates on flow resistance is shown in Figure 7. Increasing the amount of coarse aggregate as a percentage of total aggregate has a moderately increasing effect on resistance until values in the range of 50% are exceeded at which point resistance rises rapidly and can lead to blockage by arching.

The appropriate operating range here is to work within that portion of the curve that is relatively flat and to avoid the steep part of the curve that can lead to blockage.

Variation in the consistency of the concrete, represented for example by slump, also causes variation in resistance as seen in Figure 8. Very fluid concretes, say with slumps 6 in. and greater, have low resistance to flow but are very susceptible to bleeding and thus blockage by arching at which point the resistance suddenly becomes excessively large and flow is stopped. Concrete with slumps in the range of 2 to 4 inches have higher resistances. Very low slump concretes, say zero-slump, have high resistance yet can be pumped under high pressure without segregation or blockage. However, zero-slump concrete is difficult to use in a pumping operation because the stiff concrete does not draw into the pump cylinders readily on the intake stroke. Also, it may be too stiff at the point of placement to consolidate well. Slumps in the practical range of 1 to 4 inches are commonly recommended for pumping concrete. For the present case, slumps of 2 to 3 inches will probably be used.

Pipeline Blockage Prevention

Blockage of concrete flow in a pipeline is variously called stoppage, plugging, clogging, refusal and other terms. There are several types of blockage. The two most important types are: (1) blockage due to bridging or arching of the aggregates across the diameter of the pipeline, and (2) stoppage, or lack of flow, that occurs when the total force of friction between the concrete and the pipe wall along the overall length of the pipeline is greater than the driving force. Other types of blockage include stoppage due to premature setting of the concrete while still in the pipeline, and that due to gradual build-up of material on the inside of the pipe wall.

A pictorial representative of pipeline blockage due to arching of the aggregates is shown in Figure 9. This is the most serious type of blockage since once it occurs it usually cannot be overcome by increasing the pumping pressure; this only makes the blockage worse by dewatering the material through bleeding. Vibration may help but cannot be depended on. Usually, the only remedy is to take the pipe apart and flush it out.

The most common causes are too wet a mix and improper aggregate gradation. Other causes are improper size and shape of aggregate. An important contributing cause may be a localized high pressure differential due, for example, to a leaky pipe joint, a partially closed valve, a sharp bend in the pipeline, or an abrupt reduction in pipe diameter. Air bubbles or voids in the pipeline will cause bleeding which may lead to blockage. The onset of arching is sudden and once initiated usually goes to completion. Therefore, conditions (concrete mix design and operating procedures) conducive to arching should be avoided by a wide margin.

High resistance to flow due to friction between the moving concrete and the pipe wall is a serious limitation in conventional concrete pumping operations on land since it demands higher horsepower pumps and limits the distance and height to which concrete can be pumped. If the

total friction force along the length of the pipeline becomes too large, the flow is stopped. However, flow can be started again by increasing the driving force--that is by pushing the concrete by a higher pressure. This is in marked contrast to blockage due to arching which, as described above, is not overcome by additional driving force, and in fact gets worse.

For the proposed application the frictional resistance will be used to advantage for limiting terminal flow velocity. The concrete falling in the long vertical pipe is driven primarily by gravity. Additional force is provided by the pump pressure which will be maintained at a positive value. The force due to pump pressure, added to the force due to gravity, can be varied and will be used as a control method. If velocity becomes too great, the pump pressure can be reduced (but still positive); if velocity becomes too low, the pump pressure can be increased.

Prevention of concrete setting (hardening) in the pipeline is an important operational consideration but is not considered to be a serious technical problem. This type of blockage is avoided by limiting the length of time between mixing the concrete and placing it. Set retarder admixtures are available for delaying the initial set for up to several hours, if needed. If the operational delay occurs after the concrete is in the pipe, the pipeline should be pumped out before initial set of the concrete occurs, and the job re-started when fresh concrete is again available.

Blockage due to build-up of mortar on the pipe wall is also controlled by operational procedures; it can be prevented by cleaning with a "go-devil" periodically, say once per hour. Build-up may be more of a problem with grouts, slurries and mortars than with concrete in plug flow. However, its possibility should be planned for and expendable cleaning devices provided.

Concrete Deposited Underwater

For the proposed application the major characteristics of interest of the concrete placed at the seafloor are: (1) the flow behavior of fresh concrete underwater, particularly the mounding behavior of the concrete placed without forms, (2) the capability of the concrete to form a continuous coherent consolidated mass without layers of water, laitance, etc., and (3) the capability of concrete to mature into a good quality structural grade material in terms of strength, density and durability.

The underwater flow behavior includes characteristics such as the distance of lateral flow, the steepness of advancing front, and the residual surface slope of the concrete after it has stopped flowing. For concrete placed without forms it is desired that the concrete be able to form a mound of concrete with surface slopes of about 1 vertical to 2 horizontal or steeper. For concrete placed in forms and with reinforcing steel the concrete should flow into the forms with a minimum of trapped water in corners, and develop adequate bond to the reinforcing steel.

Upon discharge from the pipe the concrete should be capable of maintaining its plastic cohesive consistency and not segregating either by washing out of cement or settling of coarse aggregates. By "structural grade" quality is meant that concrete will develop a 28-day compressive strength of say at least 2,500 psi in the deep ocean environment and that the concrete have good durability.

Concrete Mixture Design

Requirements. The desired concrete properties are: (1) that the fresh concrete be pumpable and pipeable under high pressure at discharge rates of 30 to 50 cu yd/hour or greater, (2) that the concrete on discharge at the seafloor will form into a coherent, consolidated mass with fairly steep slopes, and (3) that the concrete will develop strength and other properties of structural grade concrete in the deep ocean environment.

The fresh concrete will need to be sufficiently plastic and cohesive to pump and to flow down the long pipe without bleeding, segregation or line blockage, and to have resistance to flow that will limit the maximum velocity to not more than about 7 to 10 ft/sec. The pumpable mix may need to have greater flow resistance (friction head loss) than usual state-of-the-art mixtures in order to use larger diameter pipes to provide the desired flow rates. Example velocities are shown in Table 4 for flow rates of interest in 3- to 4-in. ID pipes.

Materials. Concreting materials are cement, fine aggregates, coarse aggregates, water and admixtures. Portland cement having a tricalcium aluminate (C_3A) content between 4 and 10% should be used. Normal weight, well-rounded stone should be used for the fine and coarse aggregate. For most cases, the water should be potable although seawater may be used. Various admixtures can be used such as low water loss admixtures of cellulose compounds or similar patented organic admixtures. Bentonite in small quantities will improve cohesiveness. Other inorganic materials such as silica flour, pozzolan and flyash may also improve cohesiveness. However, air entrainment should not be used because the high pressures will collapse the air bubbles and alter the consistency of the mix. Set retarders may be needed to prevent premature set or to control temperature rise due to cement hydration, especially for very large pours.

Proportioning the Concrete Mixture. Mixtures will be proportioned by the minimum voids approach so that all voids are filled and excess water made available so that a saturated mix can be maintained. The water/cement ratio will be about 0.45 or possibly greater to assure the saturated condition. Cement content will be approximately 7 sacks per cubic yard. The maximum size of coarse aggregate will be equal or less than one quarter the pipe inside diameter and will be limited to a maximum size of three quarter inches in most cases. The fine aggregate ratio will be about 45 to 50%. The fine aggregate gradation will conform to ASTM Designation C33 with the additional requirements that between 15

and 30% pass the number 50 sieve and 5 to 10% pass the number 100 sieve and that the fineness modulus of the fine aggregate be in the range of 2.4 to 3.0. The coarse aggregate gradation will conform to ASTM Designation C33 as close to the middle range as feasible. The combined aggregates will be well graded with no gap grading. The air content will be minimized (Ref 10 and 19).

COST ESTIMATE

The cost of an operation to place a large quantity of concrete in the deep ocean can be roughly estimated and compared to that of a similar grouting operation. These costs can also be compared to a generalized estimate that would represent a major salvage operation.

Material costs are less for concrete than for grout because less cement is used. Table 5 shows this comparison. For a job requiring 10,000 cu yd, which would be a task equivalent to encasing a ship-sized object, the material cost is about $300,000 for concrete, $460,000 for a sand/cement grout and $630,000 for a neat cement grout.

The unit weight of concrete is considerably greater than the unit weight of grout. Table 6 compares the total quantity of material for a task that requires a submerged weight of 25 million pounds which is beyond deep water lifting capability. A 25,000,000-lb submerged weight could be provided by 10,000 cu yd of concrete or 15,000 cu yd of cement slurry. For this case, the material costs are $300,000 for concrete, $550,000 for a sand/cement grout, and $940,000 for a neat cement grout.

Material costs are important; however, at-sea operational costs are more significant in controlling overall project costs. It is difficult to quantitatively define some of these costs but qualitatively they may be compared. For instance, the logistics of supplying materials to the surface platform is a major factor. A drill ship will carry about 850 cu yd of cement. One cubic yard of cement makes 3.6 cu yd of concrete, 1.8 cu yd of sand/cement grout or 1.2 cu yd of neat cement grout. An offshore resupply boat normally carries about 350 cu yd of cement but can be outfitted with portable tanks to carry up to 800 cu yd of cement. An aggregate barge towed by a tug will supply the aggregate. A barge of 2,600 DWT capacity is assumed. Table 7 shows that fewer resupply trips are required to supply the cement and aggregate for concrete than to supply just cement or cement and sand for grout. Depending on the distance from land, fewer resupply trips can save tens to hundreds of thousands of dollars.

Time on-site while placing the material will affect the overall cost because drill ships lease at about $30,000/day. It has been stated in a previous section that the flow rate for concrete was estimated at 30 to 50 cu yd/hr using the method presented herein. For 10,000 cu yd, this equates to 8 to 14 days of continuous, round-the-clock operations. (This time could be shortened by using multiple pipes instead of just one pipe.) It is considered likely that the flow rate for grout would

be about equal to that of concrete because the pipe diameter for grout would be smaller but the velocity of flow could be greater. The operational time for actually placing either concrete or grout would be about the same; hence, these costs would be similar.

Another item in the comparison between concrete and grout that strongly favors concrete is whether or not a task can be performed without formwork. For an encasement operation, grout would require formwork of some kind to contain the material. Without formwork the grout, being a slurry, would run horizontally while producing little vertical rise. Using concrete there is the ability to place the material in thicker lifts. Concrete is able to attain a steeper slope than grout even when both materials appear equally "stiff" in a mixer. The large aggregate in concrete provides an interlocking capability that permits self-standing.

By avoiding the need for formwork, a major at-sea operation is eliminated. The additional time and cost for placing formwork could conceivably equal that of the operation to place the grout, thus doubling the overall cost. Hence, for this feature alone the development effort for concrete is justified.

To summarize, the cost of an encasement operation using concrete to cover a large object is given below as a rough estimate:

	Cost
Materials (10,000 cu yd at $30/cu yd)	$ 300,000
Material supply (8 round trips at 2 days each at $5,000/day)	80,000
Equipment rental (cement tanks, concrete mixers and pumps, batching equipment, etc.)	70,000
Drill Ship (30 days at $30,000/day)	900,000
Set up charges	100,000
Engineering and Management	300,000
Profit	250,000
	$2,000,000

The total cost would be about $2 million. This is a unit price of $200/cu yd of concrete in place, which is comparable to typical construction costs of about $300/cu yd for concrete structures but far below offshore platform costs of about $700/cu yd.

To perform a similar encasement operation by using grout the cost varies substantially if formwork is used. Without formwork, the cost is estimated at $2,400,000. With formwork, the cost of the forms and the time at sea to place the forms, results in a total cost estimated at $4,000,000.

All of the costs are attractive when compared to a salvage operation. The operation to salvage the Russian submarine using the Glomar Explorer cost over $400 million, which includes the cost of building the vessel, barge, and recovery claw. The Glomar Explorer was recently refitted for mining operations at a cost of $50 million. The barge is being refitted for ocean thermal energy experiments by the Department of Energy. The recovery claw has, reportedly, been scrapped. If the Glomar Explorer and its auxiliary equipment were to be recommissioned for another submarine recovery task, the cost would be on the order of $100 million. Also, the response time would be quite slow.

The Navy's Large Object Salvage Program (LOSS) is directed toward salvage as one of the primary operational tasks. The system uses pontoons having a lift capability of 100 long tons each at a depth of 850 feet. The depth limitation is severe when compared to Glomar Explorer's capability to lift a 2,800-ton submarine from 17,000 ft, or to place concrete at 20,000 ft for encasement purposes. However, within 850 ft the LOSS system would probably be used to recover a large object. The final cost of the recovery operation might not be less than that of an encasement operation, but at times there is value in having the damaged object available for study.

Thus, it appears from a cost and operational standpoint that concrete placement is a desirable capability for the Navy to have at its disposal.

SUMMARY

The proposed method to place concrete at deep ocean depths is considered to be technically and operationally feasible. The general approach is to mix the concrete on a surface platform and convey the concrete to the seafloor by a pipeline suspended from the platform. The task becomes more complicated in the details, but an integration of technologies from the concrete industry, the oilwell industry, and the ocean industry enables the task to be accomplished using, for the most part, state-of-the-art knowledge and hardware.

The preferred surface platform is a drill ship, which is already outfitted for most of the operational requirements except the concreting equipment, but other platforms may be used. For example, a barge can be outfitted with the necessary equipment including a portable drill rig to handle the pipestring.

Two hardware items need to be specially designed and fabricated. They are the concreting head at the input end of the pipeline and the concrete discharge device at the lower end of the pipe. Both items are straightforward design tasks with little development risks.

Conveying concrete by pipeline to deep depths places the concrete under conditions that are beyond previous experience, so its behavior needs to be verified by test. Specifically, the concrete will be flowing

downward through a very long pipe at considerably higher velocities and pressures than encountered on land. Data are needed on the rheology of concrete under these conditions with primary interest on friction head loss properties and resistance of the mix to de-watering. The material behavior research is considered to involve low technical risk, but is needed to verify engineering assumptions based on extrapolation of existing knowledge to the new conditions.

The need to develop the capability to place concrete in deep water lies in three areas of potential applications: construction of massive anchors and foundations in situ for fixed ocean facilities, encasement of objects on the seafloor, and containment of hazardous substances for environmental protection. Of these applications, the ability to encase an object in concrete and thus deny others the opportunity to inspect or recover it appears to have merit. This non-salvage approach offers rapid response time at relatively low cost.

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Table 1. Bulk Materials Storage Requirements

Item	Volume of Concrete (cu yd)		
	250	1,000	10,000
Weight of Materials			
Aggregates (lb)	760,000	3,040,000	30,400,000
Cement (lb)	160,000	640,000	6,400,000
Water (lb)	80,000	320,000	3,200,000
Total (lb)	1,000,000	4,000,000	40,000,000
Material Storage Volume			
Aggregates (cu ft)	8,000	32,000	320,000
Cement (cu ft)	2,100	8,500	85,000
Water (cu ft)	1,300	5,200	52,000
Total (cu ft)	11,400	45,700	457,000

Table 2. Oil-Well Tubing

Nominal Size (in.)	3-1/2	4	4-1/2
Approximate Internal Diameter (in.)	3.0	3.5	4.0
Submerged Weight of Pipe Filled With Concrete (lb/1,000 ft)	12,400	15,400	18,700

Table 3. Major Factors for Deep Ocean Concreting

1. <u>Concrete</u>

   Concrete materials' characteristics
   Concrete mixture proportioning
   Fresh concrete characteristics (water retention capability; density; consistency as measured by slump, flow table or other means; changes under high pressure)
   Behavior of concrete after discharge underwater at seafloor (flow; angle of repose; degree of consolidation; formation of laitance; time to initial set; temperature rise; strength when hardened)

2. <u>Flow Characteristics</u>

   Discharge rate (cu yd/hour)
   Type of flow (plug, laminar or turbulent)
   Velocity of flow
   Resistance to flow ("friction head loss")
   Blockage of pipe

3. <u>Pipe</u>

   Strength (tensile, burst, collapse)
   Weight
   Internal diameter
   Internal smoothness, including smoothness at joints

4. <u>Environment</u>

   Hydrostatic pressure
   Temperature

5. <u>System and Operational Considerations</u>

   Ocean platform; weight and pipe handling equipment; positioning systems; concreting equipment; materials storage; concreting, pipehandling, and ship's crew; total weight of deployed pipeline filled with concrete

6. <u>Application Requirements</u>

   Purpose of concreting
   Concrete considerations (total quantity of concrete; dimensions and shape; forms)
   Site considerations (water depth; seafloor characteristics; geographical location; weather and sea state)

7. <u>Costs</u>

   Costs of concrete in place (including costs of the total operation for the given application)
   Comparative costs of in situ concreting compared to alternatives

Table 4. Calculated Flow Velocities and Friction Values

Concrete Discharge Rate (cu yd/hr)	Velocity (ft/sec) of Flow for Pipe of Inside Diameter Shown:		
	3 in.	3.5 in.	4 in.
60	9.2	6.7	5.2
50	7.6	5.6	4.3
40	6.1	4.5	3.4
30	4.6	3.4	2.6

NOTE: The theoretical frictional shear stress between the flowing concrete and the pipewall that is required to balance the net downward force due to gravity is 0.037 psi of pipe interior surface area for a 3.0-in. ID pipe, 0.044 psi for a 3.5-in. ID pipe, and 0.050 psi for a 4.0-in. ID pipe.

Table 5. Material Cost for a Quantity of 10,000 Cubic Yards of Concrete

Material	Cement (lb/cu yd)[a]	Aggregate (lb/cu yd)[b]	For 10,000 Cu Yd of Concrete				
			Cement (lb x 10^6)	Cost of Cement[c] ($)	Aggregate (lb x 10^6)	Cost of Aggregate[d] ($)	Total Cost of Material ($)
Concrete	700	3,000	7	210,000	30	90,000	300,000
Sanded Grout (sand/cement ratio = 1.0)	1,400	1,400	14	420,000	14	40,000	460,000
Neat Cement Grout	2,100	0	21	630,000	0	0	630,000

[a] lb of cement per cu yd of concrete

[b] lb of aggregate per cu yd of concrete

[c] at $0.03/lb

[d] at $0.003/lb

Table 6. Material Cost for a Submerged Weight of 25,000,000 Pounds

Material	In-Air Unit Weight[a] (lb/cu ft)	Submerged Unit Weight[a] (lb/cu ft)	For 25,000,000 Lb Submerged Weight	
			Quantity (cu yd)	Material Cost ($)
Concrete	155	91	10,000	300,000
Sanded Grout (sand/cement ratio = 1.0)	140	76	12,000	550,000
Neat Cement Grout	125	61	15,000	940,000

[a]These values include 5 lb/cu ft for having all voids filled with water, which would be the case for the material on the seafloor.

Table 7. Number of Delivery Trips to Supply Materials

Material	Cement Required (cu yd)	Number of[a] Trips for Cement Barge	Aggregate Required (cu yd)	Number of[b] Trips for Aggregate Barge	Total Trips
For 10,000 Cu Yd of Concrete					
Concrete	2,760	3	9,300	5	8
Sanded Grout (sand/cement ratio = 1.0)	5,520	6	4,300	3	9
Neat Cement Grout	8,270	10	0	0	10
For 25,000,000 Lb Submerged Weight					
Concrete	2,760	3	9,300	5	8
Sanded Grout (sand/cement ratio = 1.0)	6,670	7	5,160	3	10
Neat Cement Grout	12,400	15	0	0	15

[a] Drill ship carries 850 cu yd cement and offshore resupply boat 800 cu yd

[b] Assuming 2,600 DWT barge which would carry 1,800 cu yd of aggregate

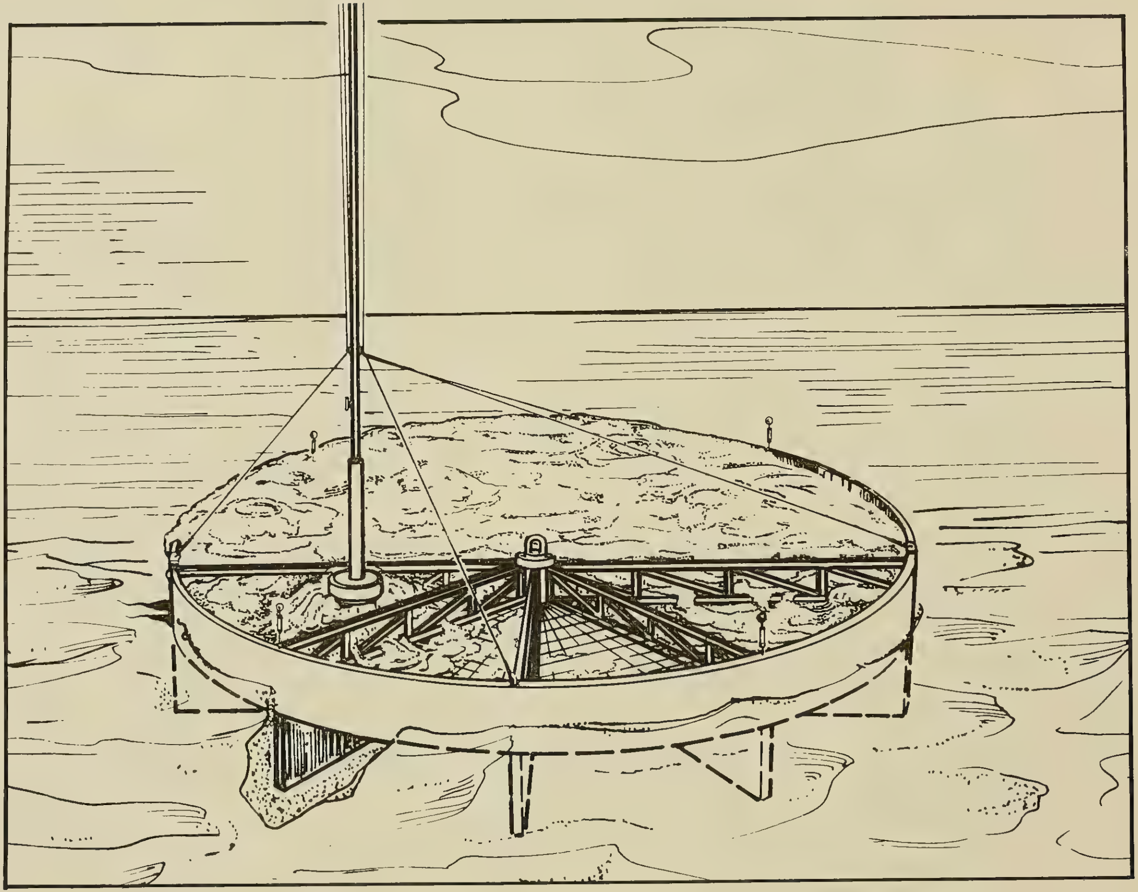

Figure 1. Concrete placement method used to fabricate multi-million pound capacity deadweight anchor.

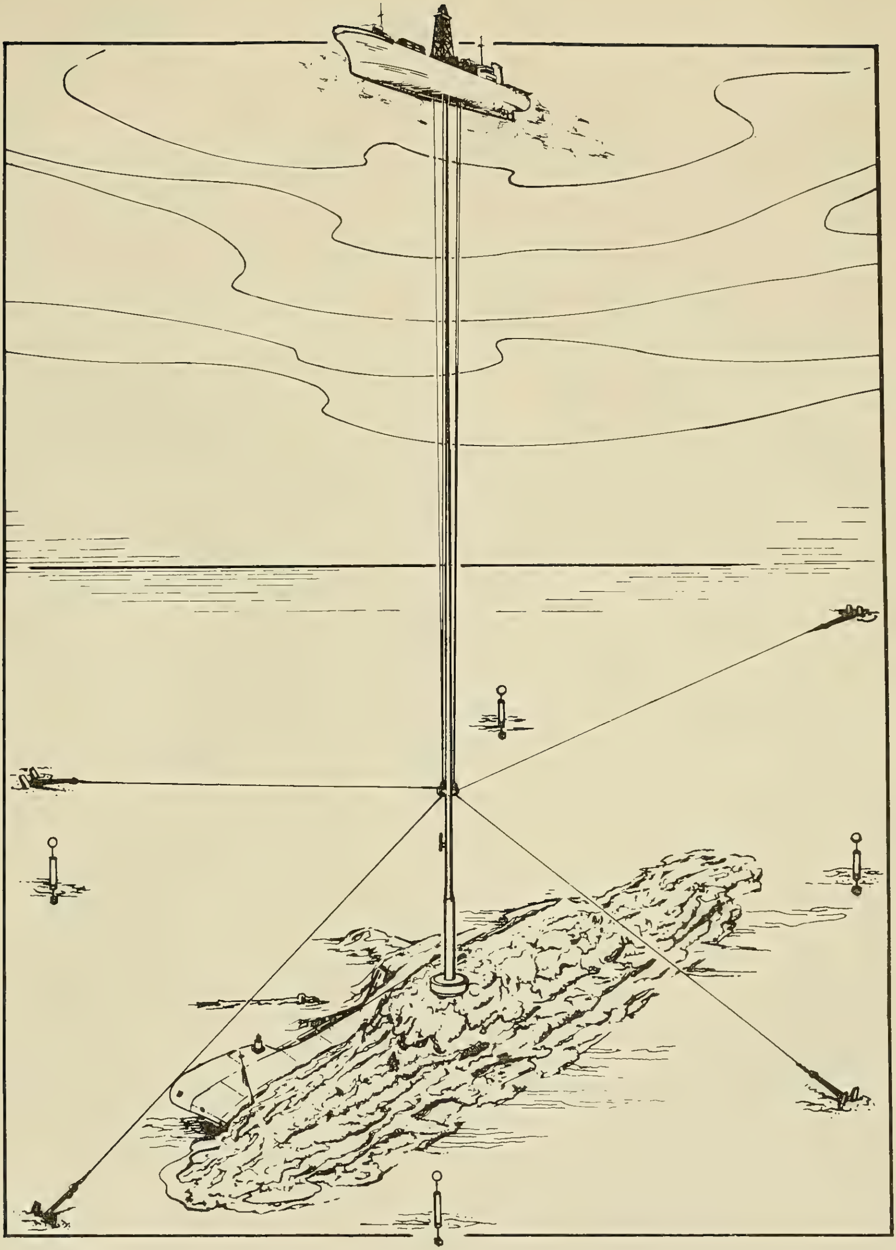

Figure 2. Overall configuration of deep concrete placement method.

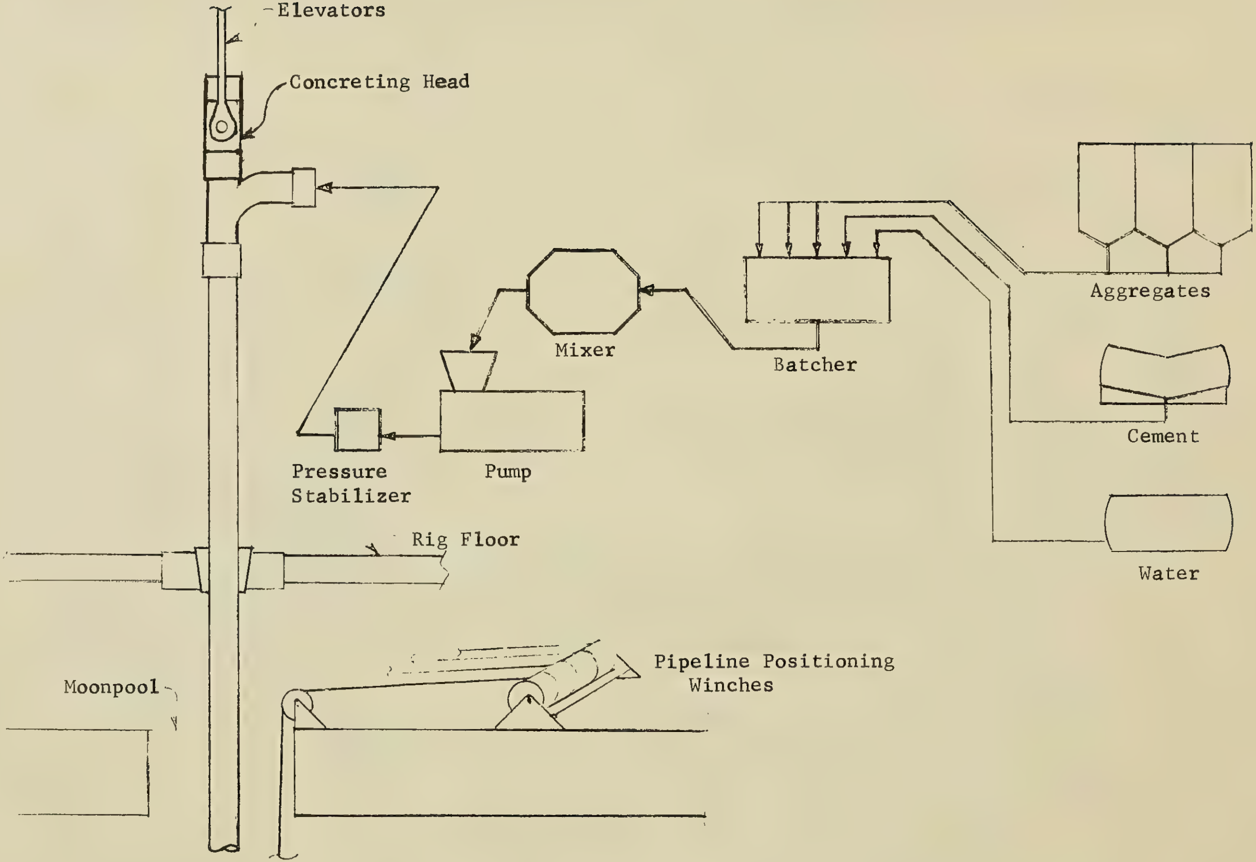

Figure 3. Concreting system on surface platform.

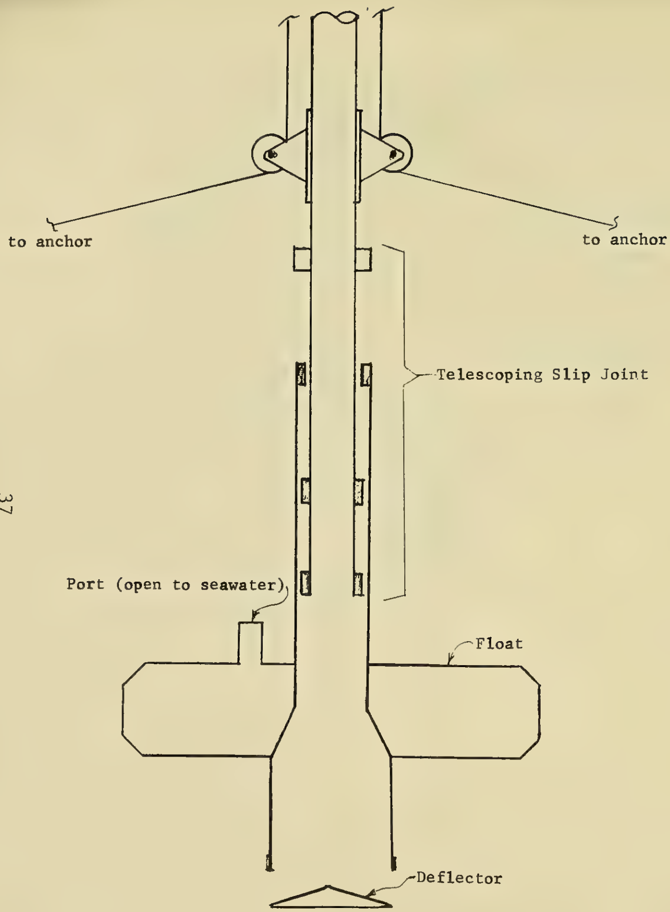

Figure 4. Seafloor discharge device.

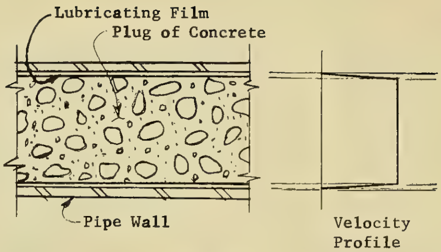

Figure 5. Plug flow of concrete in a pipeline.

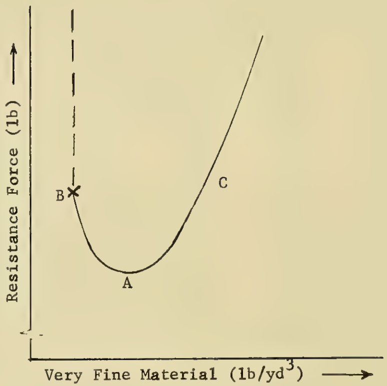

Figure 6. Effect of amount of very fine material on flow resistance. "Very fine material" includes cement and fine aggregate passing No. 200 sieve (after Reference 16).

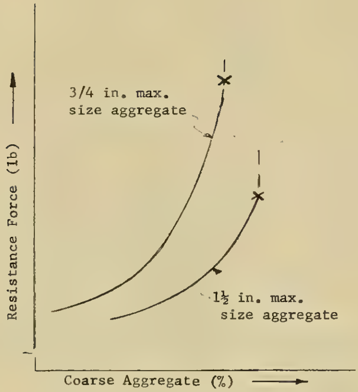

Figure 7. Effect of amount of coarse aggregate, as percent of total aggregate, on flow resistance (after Reference 16).

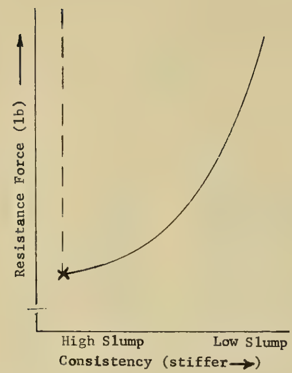

Figure 8. Effect of concrete consistency on flow resistance (after Reference 16).

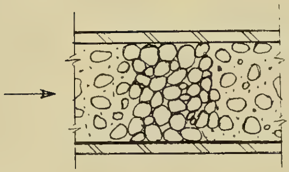

Figure 9. Arching of aggregates across the diameter of a pipe due to de-watering.

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